

Strange Mesonic Transition Form Factor in the Chiral Constituent Quark Model

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Abstract

The form factor $g_{\rho\pi}^{(S)}(Q^2)$ of the strange vector current transition matrix element $\langle \rho | \bar{s} \gamma_\mu s | \pi \rangle$ is calculated within the chiral quark model. A strange vector current of the constituent U - and D -quarks is induced by kaon radiative corrections and this mechanism yields the nonvanishing values of $g_{\rho\pi}^{(S)}(0)$. The numerical result at the photon point is consistent with the one given by the ϕ -meson dominance model, but the fall-off in the Q^2 -dependence is faster than the monopole form factor. Mesonic radiative corrections are also examined for the electromagnetic ρ -to- π and K^* -to- K transition amplitudes.

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INTRODUCTION

The strangeness content of the nucleon is a subject of growing interest in nuclear and particle physics. From an empirical analysis [1] of the baryon octet masses, it is inferred that a significant portion of the nucleon mass is generated by the strange quarks: $m_S < N|\bar{s}s|N > \simeq 130$ MeV [2]. Nevertheless, conventional nucleon and nuclear structure models have generally omitted explicit consideration of $s\bar{s}$ degrees of freedom. The validity of this practice will be tested, in part, by several experiments measuring the distributions of the strange-quark vector ($\bar{s}\gamma^\mu s$) and axial vector ($\bar{s}\gamma^\mu\gamma^5 s$) currents inside the nucleon by means of parity-violating (PV) elastic electron-proton or electron-nucleus scattering [3–7] and by elastic neutrino-nucleon scattering [8], respectively. PV elastic electron scattering from $(J^\pi, T)=(0^+, 0)$ nuclei is of particular interest because in this case the strangeness contribution to the helicity asymmetry nominally depends only on the strange electric form factor of the nucleon G_E^S [9] (relativistic corrections introduce a weak dependence on the magnetic form factor, G_M^S [13]). This situation follows from the spin-isospin quantum numbers for this particular type of nucleus. Moreover, one expects nuclear structure effects, such as the isospin-mixing in the wave function, to be negligible in the cases of the light nuclei [10]. With these considerations in mind, direct measurements of G_E^S are planned at TJNAF with ^4He nucleus as the target [5,6].

Recent theoretical studies, however, have pointed out the prospective importance of the meson exchange current (MEC) contribution to the ^4He strangeness form factor. Of particular relevance is the ρ -to- π transition MEC [11]. Unlike the purely pionic and $N\bar{N}$ MEC's, which depend on the single nucleon strangeness form factors [13,14], the ρ -to- π current arises from non-nucleonic strange-quarks through the amplitude $\langle \rho|\bar{s}\gamma_\mu s|\pi \rangle$. With the use of a realistic nuclear wave function obtained in the variational Monte Carlo method [12], it has been found that the transition MEC and one-body current may have comparable magnitudes near the expected kinematics of the experiment of Ref. [5]: $Q^2 = 0.6$ (GeV/c) 2 [13]¹. Consequently, a reliable extraction of the nucleon strangeness form factors from the ^4He PV asymmetry requires knowledge of both the magnitude of $g_{\rho\pi}^{(S)}(Q^2)$ as well as the degree of model dependence associated with theoretical estimates.

In this note, we compute $g_{\rho\pi}^{(S)}(Q^2)$ using a model which complements those used in previous calculations. Our aim is not to arrive at a definitive prediction for this form factor, but rather to obtain an estimate which, when compared to results of other calculations, will help to determine the scale of model dependence in the corresponding MEC. In conventional analysis, the MEC operator itself depends on the amplitude of the ρ -to- π strange vector current transition:

$$< \rho(p+q, \varepsilon) | \bar{s}\gamma^\mu s | \pi(p) > = \frac{g_{\rho\pi}^{(S)}(Q^2)}{m_\rho} \epsilon^{\mu\nu\alpha\beta} p_\nu q_\alpha \varepsilon_\beta^* \quad (1)$$

where ε_β is the polarization of ρ meson. This amplitude is off-diagonal, so that no conservation principle constrains the form factor $g_{\rho\pi}^{(S)}(Q^2)$ at the photon point ($Q^2 = 0$). In the

¹This result assumes that the single nucleon form factor yields a strangeness radius of the scale given by pole model calculations [15]

absence of its direct measurement one must rely on theoretical models for $g_{\rho\pi}^{(S)}(Q^2)$. Ideally, such models should also yield a reasonable explanation of known observables, such as the electromagnetic form factor $g_{\rho\pi}^{(EM)}(Q^2)$. Along these lines, two theoretical estimates of the strange vector ρ -to- π transition amplitude have been reported, both using a hadronic framework: one with the ϕ -meson dominance model [14] and the other with the K^*K loop model [16].

In the present paper, we calculate $g_{\rho\pi}^{(S)}(Q^2)$ with the chiral constituent quark model [17], where the Goldstone bosons couple to the constituent quarks in a chiral invariant manner. The mass spectrum [18] and electromagnetic form factors [19,20] of nonstrange baryons and mesons are well explained with the constituent quark model, where the hadrons are composed of the weakly interacting nonstrange constituent quarks. With this successful effective description of QCD on the one hand and the empirical observation [2] of the nucleon's strangeness content on the other, one would expect the nonstrange constituent quarks may have complex structure including $\bar{s}s$ pairs as a component [21]. In the chiral quark model, this effect is taken into account via kaon radiative corrections which induce a "strangeness polarization" of the nonstrange quarks: $U \rightarrow K^+ + S \rightarrow U$ and $D \rightarrow K^0 + S \rightarrow D$. This mechanism of flavor changing mesonic radiative corrections also modifies the electroweak couplings of constituent quarks, and we examine such effects on both vector strange and electromagnetic current processes in the same framework. Although the model faces some conceptual ambiguities [22], it has, nevertheless, enjoyed considerable success in describing a variety of low-energy nucleon properties [17,23–25]. We therefore treat it as a useful, though not definitive, tool for estimating the scale of flavor mixing in constituent quarks.

In the framework of constituent quark models, the strangeness distribution in a non-strange quark can be described in terms the strange vector current of the U and D quarks, defined as [26]

$$J_S^\mu = f_1^{(S)}(Q^2)\gamma^\mu + \frac{i}{2M}f_2^{(S)}(Q^2)\sigma^{\mu\nu}q_\nu, \quad (2)$$

where $Q^2 \equiv \mathbf{q}^2 - q_0^2$ is the momentum transfer, and $M = M_u \simeq M_d \sim 300$ MeV is the constituent quark mass. Since the net strangeness is zero for these quarks, the Dirac form factor vanishes at the photon point ($f_1^{(S)}(0) = 0$), but the anomalous magnetic moment is subject to the renormalization ($f_2^{(S)}(0) \neq 0$) due to the cloud of K -mesons.

In the absence of the Dirac form factor, the ρ -to- π transition amplitude given by the quark model matrix element of J_S^μ is proportional to $f_2^{(S)}(0)$ (up to corrections) at the photon point

$$g_{\rho\pi}^{(S)}(0) = \alpha f_2^{(S)}(0) + \cdots, \quad (3)$$

where α depends on the quark distributions in the hadrons. Higher order terms may arise from many-body currents and correlations. For purposes of arriving at an estimate, however, retention of only the one-body terms is sufficient. With the use of the strangeness current in Eq. (2) we calculate the form factor $g_{\rho\pi}^{(S)}(Q^2)$ by using the relativistic quark model wave function. The first step is to evaluate the constituent quark form factors $f_i^{(S)}(Q^2)$ by calculating the vertex correction at the quark coupling to the electroweak neutral boson in Figures 1b-1g (also Fig.1 in [27,28]). We subsequently evaluate the matrix element of J_S^μ

using appropriate flavor-spin-space wave functions. A similar approach has been followed in estimating the nucleon's strange magnetic moment ($G_M^S(0)$)

$$G_M^S(0) = \beta f_2^{(S)}(0) + \dots, \quad (4)$$

where β can be obtained from the quark model wave function of the nucleon [26–28].

MODEL

The $SU(3)_L \times SU(3)_R$ chiral symmetry of three-flavor QCD is spontaneously broken at the level of the quark and gluon degrees of freedom, yielding the so-called “soft” mass ($\sim M$) [17,29] and the appearance of the octet Goldstone bosons. The chiral quark model [17] incorporates this aspect by introducing the non-linear fields of interacting Goldstone boson octet (φ) that couple to the constituent quark field (ψ)

$$\mathcal{L} = i\bar{\psi}(\mathcal{D}_\mu + V_\mu)\gamma^\mu\psi - \bar{\psi}\mathbf{M}\psi - g_A\bar{\psi}A_\mu\gamma^\mu\gamma^5\psi + \frac{f_\pi}{4}\text{tr}\{\partial^\mu\Sigma^\dagger\partial_\mu\Sigma\} + \dots \quad (5)$$

where $V_\mu = \frac{1}{2}(\xi^\dagger\partial_\mu\xi + \xi\partial_\mu\xi^\dagger)$, $A_\mu = \frac{i}{2}(\xi^\dagger\partial_\mu\xi - \xi\partial_\mu\xi^\dagger)$ and $\Sigma = \xi^2$ with $\xi = e^{i\varphi/f_\pi}$. Here, $\mathbf{M} = \{M_U, M_D, M_S\}$ is the diagonal mass matrix of the constituent quarks, $f_\pi = 93\text{MeV}$ is the pion weak decay constant, and the covariant derivative \mathcal{D}_μ includes the gluon fields. The octet of the Goldstone boson fields is expressed in a matrix form in the quark-flavor space,

$$\varphi = \frac{1}{\sqrt{2}} \begin{bmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & \frac{-1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & \frac{-2}{\sqrt{6}}\eta \end{bmatrix}. \quad (6)$$

The strange vector current is obtained by the minimal substitution of the external source coupling to strangeness, \mathcal{Z}_μ : $\partial_\mu \rightarrow \partial_\mu + i\omega_S\mathcal{Z}_\mu$ for each field with the strangeness ω_S . The strangeness form factors $f_1^{(S)}(Q^2)$ and $f_2^{(S)}(Q^2)$ are calculated from the diagrams of the K -meson loop expansion [28], which are the lowest order in $\frac{1}{N_C}$ ($\sim \frac{1}{f_\pi^2}$). The matrix element of the strange vector current for the ρ -to- π transition is given by the sum of Fig.1b,c,d,e,f and Fig.1g, where one of the nonstrange quarks turns into the strange quark accompanied with the K meson cloud; $U(D) \rightarrow S + K \rightarrow U(D)$, and the external neutral current couples to the strangeness.

The loops of Figs. 1b-k are U.V. divergent, and one may remove such divergences through the appropriate higher-order terms in the chiral Lagrangian (see, *e.g.*, Eq. (46) of Ref. [27]). In general, the finite components of these counter-terms may be determined from existing data using chiral symmetry. In the case of the strangeness form factors of a non-strange constituent quark, however, such a determination is not possible [27]. An alternate strategy is to cut the loop-momentum off at the scale of the chiral symmetry breaking $\Lambda = \Lambda_\chi \sim 1$ GeV. We implement this procedure in a gauge-invariant way by introducing a monopole form factor $(\Lambda^2 - \mu^2)/(\Lambda^2 - k^2)$ at the quark-meson vertex, where k is the four momentum of the meson and μ is the mass. The gauge invariance is minimally satisfied for the sum of the amplitudes Fig.1b, c, d and Fig.1e, where the last two terms are associated with the momentum dependence of the meson-quark vertex. The quarks also couple to the vector fields of the Goldstone bosons by $\bar{\psi}V_\mu\gamma^\mu\psi$, and this vertex induces the amplitudes Fig.1f

and Fig.1g in the same order of the expansion. The sum of these two are gauge invariant by itself.

The hadronic matrix element [Eq. (1)] of the strange vector current in Eq. (2) is dominated by the anomalous magnetic moment term, and this term is of the relativistic order ($\sim q/M$). The use of the light-cone quark model has been quite successful in predicting the electromagnetic [19,20] and strangeness [26,27] form factors of hadrons including the off-diagonal meson form factors of the $\gamma + \pi \rightarrow \rho$ and $\gamma + K \rightarrow K^*$ transitions [31–33], and we follow the method of Ref [30] in this work. The $+$ component of a vector current ($j^+ \equiv j^0 + j^3$) is commonly used in the light-cone approach, and with this choice the phenomenological form of the transition amplitude in Eq. (1) becomes

$$\langle \rho^a(p', \varepsilon) | j^+ | \pi^b(p) \rangle = \frac{g_{\rho\pi}^{(S)}(Q^2)}{m_\rho} p^+ [\varepsilon^* \times \mathbf{q}]_z, \quad (7)$$

where $p^+ \equiv p^0 + p^3$. The four momentum of the π meson moving toward the z -direction is $p^\mu = (m_\pi^2/p^+, \mathbf{0}, p^+)$ and the one of the ρ meson in the final state is $p'^\mu = ([\mathbf{q}_\perp^2 + m_\rho^2]/p^+, \mathbf{q}_\perp, p^+)$ with the light-cone representation of a four-vector $V^\mu = (V_-, \mathbf{V}_\perp, V_+)$. The photon momentum satisfies $q^2 = -\mathbf{q}_\perp^2$ with $\mathbf{q}_\perp = (q_x, q_y, 0)$. The transverse (ε_T) and longitudinal (ε_L) polarization vectors of the ρ meson are

$$\varepsilon_T(p') = (2\varepsilon_\perp \cdot \mathbf{q}_\perp / p^+, \varepsilon_\perp, 0) \quad (8a)$$

$$\varepsilon_L(p') m_\rho = ([\mathbf{q}_\perp^2 - m_\rho^2] / p^+, \mathbf{q}_\perp, p^+) \quad (8b)$$

where $\varepsilon_\perp \equiv \varepsilon_\perp^\oplus = (\frac{-1}{\sqrt{2}}, -\frac{i}{\sqrt{2}}, 0)$ for the positive helicity state, where $\varepsilon_T \cdot p' = \varepsilon_L \cdot p' = 0$ is satisfied [34]. Note that only the transversely polarized ρ meson can contribute to the matrix element ($\varepsilon_L \times \mathbf{q}_\perp = 0$). In this frame, a vector current expressed with the Dirac matrices can be reduced to the Pauli matrix form: $J_S^+ \Rightarrow j^+ = 2\{f_1^{(S)}(Q^2)I + \frac{i}{2M}f_2^{(S)}(Q^2)[\sigma \times \mathbf{q}_\perp]_z\}$, and the matrix element of the transition amplitude is explicitly calculated with the use of the quark model wave functions (Ψ_π and Ψ_ρ)

$$\begin{aligned} \langle \rho^a(p', \varepsilon) | j^+ | \pi^b(p) \rangle &= \frac{2p^+}{16\pi^3} \int dx \int d^2k_\perp \frac{1}{x(1-x)} \\ &\times \sum_{s_a, s_{a'}, s_b} \Psi_\rho^\dagger(s_b, s_{a'}) \{f_1^{(S)}(Q^2)I + \frac{i}{2M}f_2^{(S)}(Q^2)[\sigma \times \mathbf{q}_\perp]_z\}_{s_{a'}, s_a} \Psi_\pi(s_a, s_b) + (a \leftrightarrow b). \end{aligned} \quad (9)$$

Here, momenta of quark (a) and antiquark (b) in the initial state are defined by $\mathbf{p}_a = x_a \mathbf{p} + \mathbf{k}_{a\perp}$ and $\mathbf{p}_b = x_b \mathbf{p} + \mathbf{k}_{b\perp}$, where $x = x_a$ and $x_b = 1 - x_a$ are the fractions of their longitudinal momenta and the transverse momenta are given by $\mathbf{k}_{a\perp} = -\mathbf{k}_{b\perp} = \mathbf{k}_\perp - \frac{1}{2}(1 - x_a)\mathbf{q}_\perp$. With a convenient choice of the photon momentum $\mathbf{q}_\perp = (Q, 0, 0)$, the wave function of the transversely polarized ρ meson $\Psi_\rho(s_b, s_{a'})$ is proportional to the y -component of the polarization vector,

$$\Psi_\rho^\dagger(s_b, s_{a'}) = \varepsilon_{\perp y}^* \mathcal{N}_\rho \langle s_b | a_0 I + a_1 \sigma_1 + a_2 \sigma_2 + a_3 \sigma_3 | s_{a'} \rangle \chi_{cf}^*(\rho) \varphi_\rho(M_0'^2) \quad (10)$$

where the quark-spin configuration of the vector meson, $\langle s_b | \cdots | s_{a'} \rangle$, is obtained from the Melosh transformation [35] of the spinor matrix element $[\bar{u}\gamma^\mu v]$ [30]. The coefficients

a_n are given by $a_0 = i(k_x'^2 - k_y'^2 - e_1' e_2')/D'$, $a_1 = (e_1' - e_2')k_y'/D'$, $a_2 = -(e_1' + e_2')k_x'/D'$ and $a_3 = -2k_x' k_y'/D'$ with $D' = \sqrt{2}d_1' d_2'$, $d_i' = \sqrt{k_{\perp i}^2 + e_i'^2}$ and $e_i' = m_i + x_i M_0'$. Here, $M_0'^2 = \sum_{i=a}^b (k_{\perp i}^2 + m_i^2)/x_i$ is the invariant mass of the quark-antiquark system. The momentum distribution is denoted by $\varphi_\rho(M_0'^2)$, and we use the gaussian function $\varphi_\rho(x) = \exp(-\frac{x^2}{2\gamma^2})$ [36]. The color and flavor wave function is denoted by $\chi_{cf}(\rho)$, for example $\chi_{cf}(\rho^+) = \chi_{cf}(\pi^+) = \frac{1}{\sqrt{N_c}} \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$ for the charged ρ and π mesons, and the normalization factor \mathcal{N}_ρ is determined by the charge normalization for the charged ρ meson. The wave function of the pion is

$$\Psi_\pi(s_a, s_b) = \mathcal{N}_\pi \langle s_a | b_0 I + b_1 \sigma_1 + b_2 \sigma_2 + b_3 \sigma_3 | s_b \rangle \chi_{cf}(\pi) \varphi_\pi(M_0^2) \quad (11)$$

where the coefficients b_n are $b_0 = -i(e_1 + e_2)k_x/D$, $b_1 = 0$, $b_2 = (k_\perp^2 - e_1 e_2)/D$ and $b_3 = -(e_1 + e_2)k_y/D$. In the present work based on the chiral quark model Lagrangian, the pion is considered to be point-like object, with pseudovector coupling to the quark-antiquark pair: $\frac{g_A}{f_\pi} p_\mu \gamma^\mu \gamma^5$. Consistency between these properties and the formalism of Eq. (9) requires that one set $\varphi_\pi(M_0^2) = \text{const}$ and $\mathcal{N}_\pi = \frac{g_A}{f_\pi} \sqrt{N_c}$ (the pion wave function is defined with the explicit color dependence $\chi_{cf}(\pi) \sim 1/\sqrt{N_c}$).

RESULTS AND DISCUSSION

We start with a discussion of the electromagnetic radiative decay of a vector to pseudoscalar meson. The numerical results for the $\rho^+ \rightarrow \pi^+ + \gamma$, $K^{0*} \rightarrow K^0 + \gamma$ and $K^{*+} \rightarrow K^+ + \gamma$ processes are presented in Table I, where we observe the major contribution from the simple quark model matrix element Fig.1a obtained with the electromagnetic current operator of point-like quark $J^\mu = e_q \gamma^\mu$. To obtain an idea of the sensitivity of these results to various model parameters, we vary the quark mass by 10% (from $M = 330$ MeV to 300 MeV). The results for the amplitudes change by about 5 – 8%. Similarly, varying the harmonic oscillator parameter of the wave function from $\gamma = 0.64 \text{ GeV}$ to 0.70 GeV reduces the amplitudes about 3 – 5%. We note that there remains an ambiguity of sign for the transition amplitudes, which depends on the relative phases of the wave function normalizations; $g_{\rho\pi}^{(EM)} \sim \mathcal{N}_\rho \mathcal{N}_\pi$. We cannot fix this phase from the experimental data for the decay rates $\Gamma_{\text{exp}} \sim |g_{\rho\pi}^{(EM)}|^2$, and we chose \mathcal{N}_ρ and \mathcal{N}_π to be real and positive in this work. The same convention is used for the calculation of the strangeness form factor $g_{\rho\pi}^{(S)}(Q^2)$.

The lowest order $\mathcal{O}(1/\Lambda_\chi^2)$ mesonic radiative corrections to the matrix element of Fig. 1a are calculated from the ten diagrams Fig.1b-Fig.1k. The pseudoscalar meson loops include the entire octet of the Goldstone bosons. These loops generate about a 6 – 10% correction to the contribution from Fig. 1a, as indicated in the third column of Table I. This correction is similar in magnitude to the variations induced by 10% changes of model parameters. (The predicted decay width Γ_{th} given in the fourth column of Table I takes into account the mesonic radiative corrections.)

For the case of the strange vector current ρ -to- π transition, we evaluate the six diagrams of Fig.1b-Fig.1g, where the loops contain K mesons only. The other diagrams (1a, h-k) do not contribute. The strangeness form factors of the U - and D -quarks are calculated with the cut-off mass of $\Lambda = 1.0 \text{ GeV}$ (1.2 GeV). The Dirac form factor $f_1^{(S)}(Q^2)$ vanishes at $Q^2=0$ and the strange anomalous moment is $f_2^{(S)}(0) = -0.030$ (–0.041) [28]. The momentum dependence of the strange vector ρ -to- π transition $g_{\rho\pi}^{(S)}(Q^2)$ is plotted in Fig.2, where we

actually present the scaled values $\bar{g}_{\rho\pi}^{(S)}(Q^2) = g_{\rho\pi}^{(S)}(Q^2)/g_{\rho\pi}^{(S)}(0)$. The value at the photon point is $g_{\rho\pi}^{(S)}(0) = -0.21(-0.27)$ for $\Lambda = 1.0$ GeV (1.2 GeV). Here the solid line is the prediction of the present work with $\Lambda = 1.0$ GeV. In the vector (ϕ) meson dominance model (VMD), this form factor can be parametrized in a monopole function

$$g_{\rho\pi}^{(S)}(Q^2) = g_{\rho\pi}^{(S)}(0) \frac{m_\phi^2}{Q^2 + m_\phi^2}. \quad (12)$$

With the empirical values of the hadronic ($\phi \rightarrow \rho\pi$) and leptonic ($\phi \rightarrow l^+l^-$) decay rates the VMD model yields the magnitude $|g_{\rho\pi}^{(S)}(0)| = 0.21$ [16], and this value has been used in calculating the $\rho\pi$ -strange MEC contribution to the PV ^4He asymmetry [13,14]. The VMD form factor Eq. (12) is also shown in the Fig.2 (dotted dash line) for the comparison. Because of the composite nature of the ρ -meson, the fall-off in the quark model form factor is faster than the one in the VMD model. At the kinematics of experiment [5] ($Q^2 = 0.6 \text{ GeV}^2/c^2$), the chiral quark model prediction is about 30% smaller than the one in the VMD model.

To summarize: We have calculated the vector strangeness form factor $g_{\rho\pi}^{(S)}(Q^2)$ and electromagnetic decay amplitudes for $\rho \rightarrow \pi\gamma$ and $K^* \rightarrow K\gamma$ within the chiral constituent quark model. The mesonic radiative corrections to the constituent quark currents – generated by the octet of the Goldstone bosons – are consistently taken into account for both processes. In the case of the EM transitions, the corrections are roughly $\leq 10\%$ of the leading term (Fig. 1a), as one would expect on general grounds [17]. The resultant predictions are in good agreement with experimental values. On the other hand, the process of Fig. 1a does not contribute in the strangeness case, and the leading order contribution arises from the kaon radiative corrections: $U(D) \rightarrow K + S \rightarrow U(D)$. The nonstrange quarks acquire the strange anomalous moment $f_2^{(S)}(0)$, and we are able to relate the strangeness form factor, $g_{\rho\pi}^{(S)}(0) \propto f_2^{(S)}(0)$ in the present approach. Our result for $g_{\rho\pi}^{(S)}(Q^2)$ differs by roughly 30% from other model estimates at the kinematics of the future ^4He PV experiment [5]. We expect the theoretical uncertainty in the corresponding MEC correction to be at least as large as the degree of model-dependence in $g_{\rho\pi}^{(S)}(Q^2)$.

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REFERENCES

- [1] T. P. Chen and R. Dashen, Phys. Rev. Lett. **26**, 594 (1971); J. F. Donoghue and C. R. Nappi, Phys. Lett. **B168**, 105 (1986).
- [2] J. Gasser, H. Leutwyler and M. E. Sainio, Phys. Lett. **B253**, 252 (1991).
- [3] MIT/Bates SAMPLE experiment 89-06, R. McKeown and D. H. Beck, contact people; D. H. Beck.
- [4] Mainz proposal A4/1-93 (1993), D. von Harrach, spokesperson.
- [5] TJNAF experiment E-91-004, E. J. Beise, spokesperson.
- [6] TJNAF experiment E-91-010, J. M. Finn and P. A. Souder, spokesperson.
- [7] TJNAF experiment E-91-017, D. H. Beck, spokesperson.
- [8] G. T. Garvey, W. C. Louis and D. H. White, Phys. Rev. **C48**, 761 (1993).
- [9] M. J. Musolf, T. W. Donnelly, J. Dubach, S. J. Pollock, S. Kowalski and E. J. Beise, Phys. Rep. **239**, 1 (1994).
- [10] S. Ramavataram and E. Hadjimichael and T. W. Donnelly, Phys. Rev. **C50**, 1175 (1994).
- [11] H. Ito and F. Gross, Phys. Rev. Lett. **71**, 2555 (1993).
- [12] R. B. Wiringa, Phys. Rev. **C43**, 1585 (1991).
- [13] M. Musolf, R. Schiavilla and T. W. Donnelly, Phys. Rev. **C50**, 2173 (1994).
- [14] M. J. Musolf and T. W. Donnelly, Phys. Lett. **B318**, 263 (1993).
- [15] R. L. Jaffe, Phys. Lett. **B 229**, 275 (1989); H.-W. Hammer, Ulf-G. Meissner, and D. Drechsel, Phys. Lett. **B 367**, 323 (1996).
- [16] J. L. Goity and M. J. Musolf, Phys. Rev. **C53**, 399 (1996).
- [17] A. Manohar and H. Georgi, Nucl. Phys. **B234**, 189 (1984).
- [18] S. Capstick, "Constituent Quark Models of Baryon Structure and Strong Decays", in Proceedings of the Nato Advanced Study Institute on Hadron Spectroscopy and Confinement Problem, (Ed. D. V. Bugg, July 1995), University of London and the University of Swansea.
- [19] P. L. Chung and F. Coester, Phys. Rev. **D44**, 229 (1991).
- [20] S. J. Brodsky and F. Schlumpf, Phys. Lett. **B329**, 111 (1994).
- [21] D. B. Kaplan and A. Manohar, Nucl. Phys. **B310**, 527 (1988); V. Bernard, R. L. Jaffe, Ulf-G. Meissner, Nucl. Phys. **B308**, 753 (1988).
- [22] The relationship between the Goldstone bosons of QCD and the lightest pseudoscalar $q\bar{q}$ bound states in this model is subject to debate. See, *e.g.*, the discussions in Ref. [17] and N. Isgur, TJNAF Report No. TH-92-31, 1992.
- [23] S. Weinberg, Phys. Rev. Lett. **65**, 1187 (1990); **67**, 3473 (1991).
- [24] D. A. Dicus, D. Minic, U. van Kolck, and R. Vega, Phys. Lett. **B284**, 384 (1992).
- [25] X. Li and Y. Liao, Phys. Lett. **B318**, 537 (1993).
- [26] H. Ito, Phys. Rev. **C52**, R1750 (1995).
- [27] M. Ramsey-Musolf and H. Ito, Phys. Rev. **C55**, 3066 (1997).
- [28] H. Ito and M. J. Musolf, Proceedings of the 7th International Conference on the Structure of Baryons, page 373, edited by B. F. Gibson *et al* (World Scientific 1996).
- [29] H. D. Politzer, Nucl. Phys. **B117**, 397 (1976).
- [30] I. G. Aznauryan, A. S. Bagdasaryan and N. L. Ter-Isaakyan, Yad. Fiz. **36**, 1278 (1982).
- [31] W. Jaus, Phys. Rev. **D44**, 2851 (1991).
- [32] I. G. Aznauryan and K. A. Oganessyan, Phys. Lett. **B249**, 309 (1990).

- [33] F. Cardarelli, I. L. Grach, I. M. Narodetskii, G. Salme and S. Simula, Phys. Lett. **349**, 393 (1995).
- [34] S. J. Brodsky and J. R. Hiller, Phys. Rev. **D46**, 2141 (1992).
- [35] H. J. Melosh, Phys. Rev. **D9**, 1095 (1974).
- [36] S. J. Brodsky, T. Huang and G. P. Lepage, Springer Tracts in Modern Physics **100**, "Quarks and Nuclear Forces" (eds. D.Fries and B. Zeitnitz) 1982.

FIGURES

FIG. 1. Quark loop diagrams for the transition form factor of the vector (double line)-to-pseudoscalar meson (dot line), where the wavy line is the electroweak neutral boson or photon. The solid line is the constituent quark.

FIG. 2. Form factor of the strange vector current ρ -to- π transition defined by $\bar{g}_{\rho\pi}^{(S)}(Q^2) = g_{\rho\pi}^{(S)}(Q^2)/g_{\rho\pi}^{(S)}(0)$. The solid line is the present result with $\Lambda = 1\text{GeV}$. The monopole form factor of the ϕ meson dominance model of Ref. [16] (dotted-dash line) is shown for comparison.

TABLES

TABLE I. Electromagnetic radiative transition amplitude of the vector (V) -to- pseudoscalar (P) meson $g_{VP}^{(th)}$ ($g_{VP}^{(0)}$) with (without) the mesonic radiative corrections. m_V is the mass of the vector meson. The theoretical (Γ_{th}) and experimental (Γ_{exp}) decay widths are shown. The harmonic oscillator parameter is $\gamma = 0.64$ GeV and the quark masses are $M_S = 0.45$ GeV and $M_U = M_D = 0.33$ GeV.

$V \rightarrow P + \gamma$	$\frac{g_{VP}^{(0)}}{m_V} [GeV^{-1}]$	$\frac{g_{VP}^{(th)}}{m_V} [GeV^{-1}]$	$\Gamma_{th} [MeV]$	$\Gamma_{exp} [MeV]$
$\rho^+ \rightarrow \pi^+ + \gamma$	0.71	0.75	0.069	0.068 ± 0.007
$K^{+*} \rightarrow K^+ + \gamma$	0.80	0.89	0.057	0.050 ± 0.005
$K^{0*} \rightarrow K^0 + \gamma$	-1.20	-1.30	0.122	0.117 ± 0.01

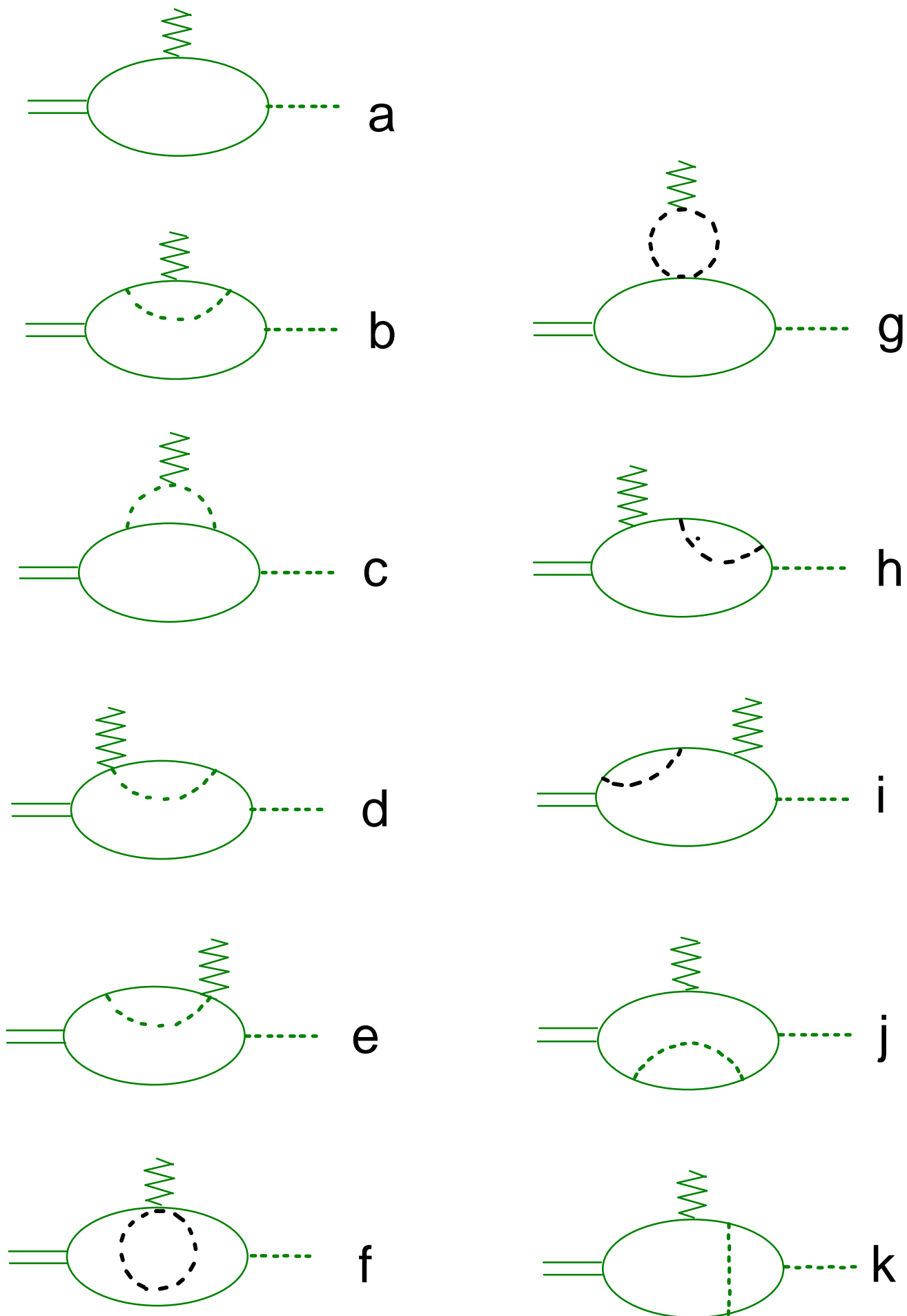


Fig.1

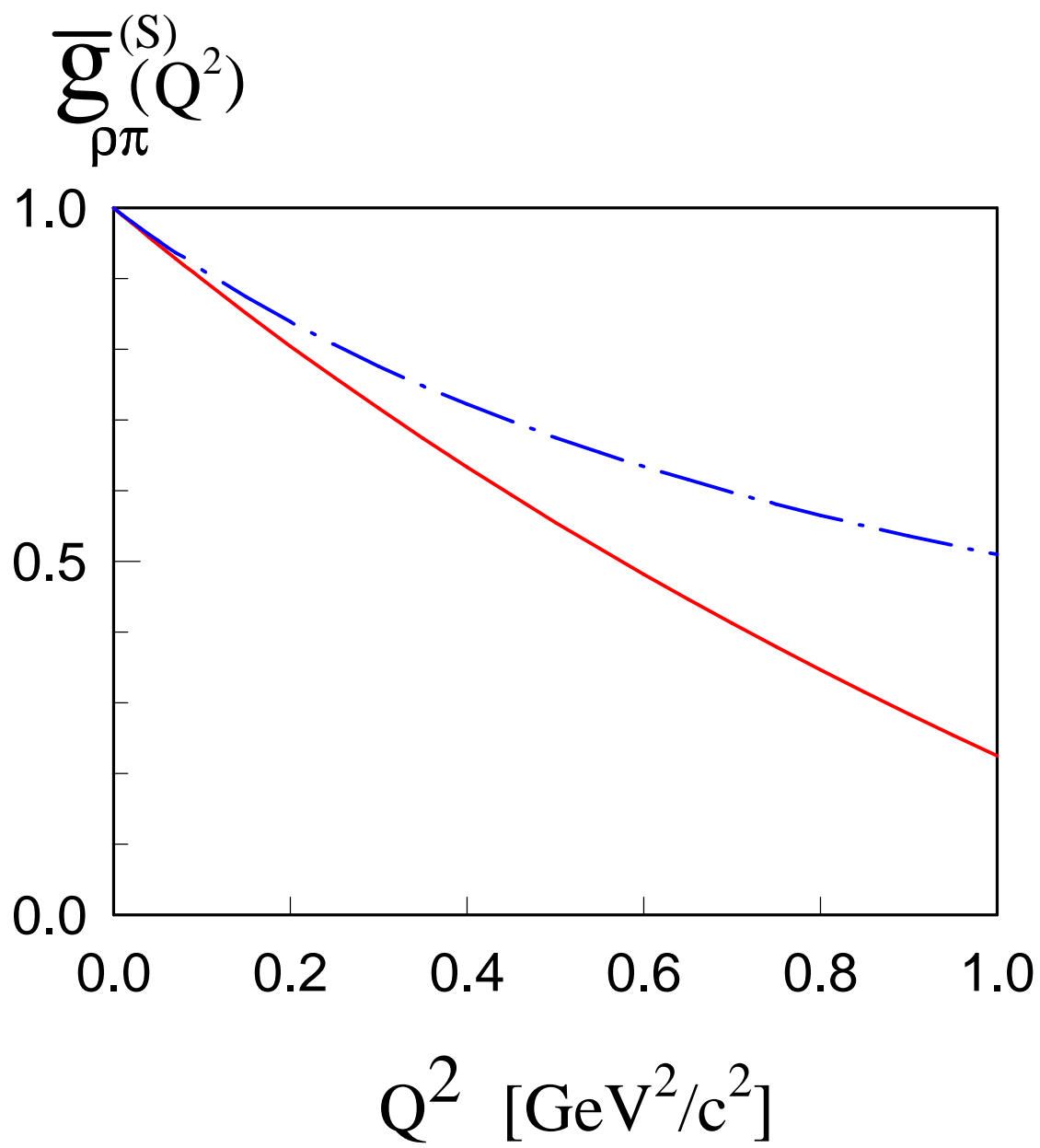


Fig.2